

The yellow hypergiants HR 8752 and ρ Cassiopeiae near the evolutionary border of instability¹

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ABSTRACT

High-resolution near-ultraviolet spectra of the yellow hypergiants HR 8752 and ρ Cassiopeiae indicate high effective temperatures placing both stars near the low- T_{eff} border of the “yellow evolutionary void”. At present, the temperature of HR 8752 is higher than ever. For this star we found $T_{\text{eff}}=7900\pm200$ K, whereas ρ Cassiopeiae has $T_{\text{eff}}=7300\pm200$ K. Both, HR 8752 and ρ Cassiopeiae have developed strong stellar winds with $V_{\infty} \simeq 120$ km s⁻¹ and $V_{\infty} \simeq 100$ km s⁻¹, respectively. For HR 8752 we estimate an upper limit for the spherically symmetric mass-loss of $6.7 \cdot 10^{-6} M_{\odot}$ yr⁻¹. Over the past decades two yellow hypergiants appear to have approached an evolutionary phase, which has never been observed before. We present the first spectroscopic evidence of the blueward motion of a cool super/hypergiant on the HR diagram.

Subject headings: Stars Individual: HR8752 — Stars Individual: ρ

Cassiopeiae — Stars: atmospheres — Stars: late-type — Stars: supergiants

¹Based on observations obtained with the William Herschel Telescope, operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

1. Introduction

Hypergiants are supergiant stars with strongly developed large-scale atmospheric velocity fields, excessive mass loss and extended circumstellar envelopes. They are rare objects, only 12 of them being known in our Galaxy. They are very luminous but are not necessarily the most luminous objects in their spectral class. The yellow hypergiants and their characteristics have been reviewed recently by de Jager (1998). There are indications (relatively small mass; overabundance of Na and N with respect to the Sun) that yellow hypergiants are evolved stars, evolving from the red supergiant phase to the blue phase. Stellar evolutionary computations (e.g. Maeder & Meynet 1988) place cool hypergiants in a certain area on the H-R diagram ($3.6 < \log T_{eff} < 3.9$, $5.3 < \log L/L_{\odot} < 5.9$) and predict that redward loops down to 4000 ± 1000 K occur only for stars with $M_{ZAMS} \leq 60 M_{\odot}$. Once in the red supergiant phase ($T_{eff} \sim 3000\text{--}4000$ K), stars with $M_{ZAMS} \geq 10 M_{\odot}$ shrink again and evolve to become blue supergiants. However, Böhm-Vitense (1958) has noted that stars with T_{eff} near 9000 K have density inversions, which may indicate instability. This has led to research on the *yellow evolutionary void*; the area on the H-R diagram which occupies the region $3.8 < \log T_{eff} < 4.0$, $5.2 < \log L/L_{\odot} < 5.9$ (de Jager & Nieuwenhuijzen 1997). The physics of this “forbidden” region for massive evolved stars on their blueward evolutionary loop has been studied recently by Nieuwenhuijzen & de Jager (1995) and de Jager & Nieuwenhuijzen (1997). Inside the void the atmospheres are moderately unstable, which is shown in various ways. The atmospheres have a negative density gradient at a certain depth level, the sonic point of the stellar wind is situated in photospheric levels, and the sum of all accelerations is directed outwards during part of the pulsational cycle (Nieuwenhuijzen & de Jager 1995). It is expected that stars, when approaching the void during their blueward evolution, may show signs of instability, but the very process of approaching the void has not yet been studied. This is a field where *no* observations have guided theory so far. A monitoring of stars approaching the void will help to understand the nature of the instabilities, the hydrodynamics of unstable atmospheres and finally to answer the most important question of whether or not these stars can pass the void.

It is believed that the Galactic hypergiants HR 8752, ρ Cas and IRC+10420 are presently “bouncing” against the “yellow evolutionary void” (de Jager 1998) at $\sim 7500 \pm 500$ K, while there were periods when they had $T_{eff} \sim 4000$ K. The brightness of IRC+10420 in V -band increased by 1 mag from 1930 to 1970 (Jones et al. 1992) and its T_{eff} has increased by 1000 K over the last 20 years (Oudmaijer et al. 1996). We do not know how rapidly they change their T_{eff} but there are some reasons to believe that these changes are accompanied by variations in the mass loss (de Jager 1998). Other hypergiants that appear to have a similar position on the HR diagram are Var A in M33 and V382 Car (Humphreys 1978). Another interesting object; HD 33579 appears to be located inside the void evolving to the red (Humphreys et al. 1991). The maximum T_{eff} ever observed in HR 8752 is 7170 K (de Jager 1999, private communication). Previous ground-based spectroscopic observations of HR 8752 and ρ Cas have been carried out only in the optical and near IR region (4000–9000 Å). High-resolution *IUE* spectra of ρ Cas and HR 8752 have been discussed by Lobel et al. (1998) and Stickland & Lambert (1981), respectively. In this letter we report first observations of these hypergiants in the near ultraviolet and communicate for the first time the finding of spectroscopically recorded large changes of the effective temperature of the cool hypergiant HR 8752 which cannot be ascribed to the regular variability of a supergiant atmosphere. This finding is based on a unique combination of high-resolution optical spectra which span a period of about 30 years. Thus, HR 8752 turned to be the first cool supergiant that showed the effects of stellar evolution from a study of its 30 years old spectroscopic history.

2. The Observations

The observations were carried out in 1998 August 4 using the Utrecht Echelle Spectrograph (UES) at the Nasmyth focus of the 4.2-m WHT at the ORM (La Palma). Two spectral images of ρ Cas and one image of HR 8752 were obtained. A UV-sensitive CCD detector EEV 42 4200×2148 (pixel size: $13.5 \times 13.5 \mu\text{m}$) with 60% quantum efficiency at 3200 Å provided superb sensitivity down to the atmospheric cut-off at 3050 Å. We obtained spectra which cover the wavelength range between 3050 and 3920 Å in 40 orders at a spectral resolving power of $R = \lambda/\Delta\lambda \sim 55,000$.

For the data reduction we used standard IRAF² procedures. The wavelength calibration was performed with a Th–Ar lamp. The final signal-to-noise (S/N) ratio varies for the different echelle orders, being in the range 80–160 for both stars. Additional high resolution spectra of these stars in the wavelength range 3500–11 000 Å were acquired with SOFIN echelle spectrograph at the 2.5-m NOT (La Palma) in 1998 October 9–10. The archival spectra from 1969 Sep. 7, 1976 July 15 and 1978 August 8 were obtained at the Dominion Astronomical Observatory, Victoria, Canada using the 1.2 m telescope in the coude focus (Smoliński et al. 1994). The dispersion of the spectrograms was about 6 Å/mm and signal-to-noise ratio at the level of 30 to 50.

3. Analysis and Conclusions

Simple comparison of the near-UV spectra of HR 8752 and ρ Cas shows that these stars are no longer spectroscopic “twins”. It is enough to overplot their spectra and to identify a number of lines in order to be convinced that the atmosphere of HR 8752 is hotter than that of ρ Cas. Most of the absorption lines in this spectral range belong to α - and Fe-group elements Ti, Si, Cr, Sc, Fe, Mn and V. In fact, the spectrum of HR 8752 is considerably *clean* from blends compared with ρ Cas because of a displacement of the ionization equilibrium. A clear illustration is presented in Fig. 1, where we compare one of the near UV echelle orders and two unblended optical Fe I lines (selected by Lobel et al. 1998) in our targets. We have also found that many absorption lines in the near-UV spectrum of ρ Cas are split. The first report of this phenomenon dates back to Bidelman & McKellar (1957). We confirm findings by Sargent (1961) and Lobel (1997) that these splits in absorption appear only in lines with $\chi_{\text{up}} \leq 3$ eV. Various explanations for the split absorption cores have been suggested in the literature. The phenomenon has been explained recently by Lobel (1997), showing that the line splitting is caused by static emission emerging from detached and cool circumstellar shells, modelled for a fast bi-polar wind.

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In order to quantify the differences in the atmospheric conditions of our targets, we have employed a grid of LTE, plane-parallel, constant flux, and blanketed model atmospheres (Kurucz 1993), computed with ATLAS9 without overshooting. These models are interpolated for several values of T_{eff} , $\log g$. For ρ Cas we used $[\text{Fe}/\text{H}]=0.3$ (Lobel et al. 1998) and for HR 8752 $[\text{Fe}/\text{H}]=-0.5$ (Schmidt 1998). Synthetic spectra were computed first, using the LTE code WITA3 (Pavlenko 1991) which takes into account molecular dissociation balance (note that our targets may have T_{eff} as low as 4000 K) and all important opacity sources. Atomic data were obtained from the VALD-2 database (Kupka et al. 1999). Our spectral window contains molecular bands of OH, CH and NH which can be used to derive CNO abundances and constrain the range of the atmospheric parameters. Molecular data for the CH (3145 Å), NH (3360 Å) and OH (0,0) (3120-3260 Å) bands were taken from Kurucz (1993), Cottrell & Norris (1978) and Israelian et al. (1998), respectively. To minimize the effects associated with errors in the transition probabilities of molecular lines, the oscillator strengths (gf -values) have been modified from their original values to match the solar atlas (Kurucz et al. 1984) with solar abundances (Anders & Grevesse 1989). Synthetic spectra of the Sun were computed using a model with $T_{\text{eff}}=5777$ K, $\log g=4.4$, $[\text{Fe}/\text{H}]=0.0$, microturbulence $\xi = 1 \text{ km s}^{-1}$.

Our first attempts to fit the spectral lines located in the CH and NH regions assuming solar CNO abundances have shown that these molecules are simply not present in the spectra. We have increased the abundance of nitrogen 10 times and still found no effect on the measured equivalent widths. This can be considered as clear evidence that both stars had $T_{\text{eff}} > 6200$ K (given the values of dissociation energies of CH, NH and OH molecules) at the time of our observation. In fact, at $T_{\text{eff}}=6200$ K we still expect 10–20 mÅ lines of the OH molecule located between 3100–3200 Å (Israelian et al. 1998) even if oxygen is slightly underabundant in ρ Cas with $[\text{O}/\text{H}]=-0.3$ (Takeda & Takeda-Hidai 1998). Given the S/N of the data, we could easily detect a minimum of 3-4 unblended OH lines if they were present in the spectra. We confirm a microturbulent velocity $\xi = 11 \pm 2 \text{ km s}^{-1}$ in both stars (de Jager 1998). Figure 2 shows the comparison between synthetic and observed spectra of both stars corresponding to the regions surrounding the CH and NH lines. We stress that these plots should not be considered as “best

fits”. We only want to show basic features and blends in these regions and demonstrate the effect of varying T_{eff} on the synthetic spectra. We did not convolve synthetic spectra with Gaussian macro-broadening (which is a combined effect of rotation and macroturbulence) because it is not affecting the EWs and therefore our final values of $T_{\text{eff}}/\log g$. However, we convolved them with a Gaussian (FWHM=0.12 Å) to reproduce the instrumental profile. The differences between the observed and calculated equivalent widths have been minimized for the best set of T_{eff} , $\log g$ and ξ (i.e. the same method as used by Lobel et al. 1998). We have selected 16 spectral lines of Sc, Cr, Ti, etc. (Fig. 2), located in the windows 3130–3170 (near the CH band) and 3340–3380 (near the NH band) and measured their EWs (typically 300–800 mÅ) with a multi-Gaussian function of the SPLOT task of IRAF. The final values of the atmospheric parameters are $T_{\text{eff}}=7900\pm200$ K and $\log g=1.1\pm0.4$ for HR 8752 and $T_{\text{eff}}=7300\pm200$ K and $\log g=0.8\pm0.4$ for ρ Cas. Because of the problem with UV opacities in presently available models of atmospheres (such as ATLAS9) with $T_{\text{eff}} \leq 7500$ K we think that the latter value can be overestimated by about 250 K (half the amplitude of T_{eff} variations caused by pulsation determined from optical spectra), since the violet wing extensions are not as strongly developed as was observed by us in Nov.-Dec. '93 (see Fig. 1).

The spectrum of HR 8752 from 1969 was analyzed with a different approach. Due to the limited spectral region, covering wavelengths from 4800 till 6060 Å, severe blending and a low signal-to-noise ratio, only a limited number of relatively unblended lines were accessible for the analysis - 27 Fe I and 6 Fe II lines. Equivalent widths were typically in range from 200 to 600 mÅ. The atmospheric parameters have been found by forcing an independence of the determined single line abundance on the excitation potential and the equivalent width, with a unique value of iron abundance for both neutral and ionized lines.

The analysis was made using atmospheric models computed with a modified version of the TLUSTY code. The use of ATLAS9 opacity sources and ODF functions enables us to treat these models as an extension of the existing grid of ATLAS9 models (Kurucz, 1993). Both plane-parallel and spherically symmetric models have been calculated. For spherically symmetric models a luminosity value of $\log (L/L_{\odot}) = 5.50$ has been utilized, as was determined by Schmidt

(1998).

The resulting parameters are $T_{eff}=5250\pm250$ K, $\log g=-0.5\pm0.5$, $[\text{Fe}/\text{H}]=-0.55\pm0.25$, microturbulence $\xi_\mu=10\pm1$ km s $^{-1}$ derived for plane-parallel models, and $T_{eff}=5630\pm200$ K, $\log g=-0.7\pm0.5$, $[\text{Fe}/\text{H}]=-0.46\pm0.25$ and $\xi_\mu=11\pm1$ km s $^{-1}$ with spherically symmetric models. For the latter case we compute that the atmospherical extension was 23 percent (being measured as the ratio of the geometrical distance between optical depths 10^{-4} and 1 and the stellar radius).

It is generally accepted that H α is the best indicator for global changes in the outer part of the envelope where the wind is accelerating in a typical cool supergiant. Variations in the velocity and density structure of the upper layers produce changes in the asymmetry of the line, while an increase of the temperature (quasi-chromosphere) can force the wing to go into emission. This effect has been clearly observed in ρ Cas (de Jager et al. 1997). However, changes in H α may reflect those in the chromospheric structure rather than wind variations. For this reason it is desirable to study wind variations in other absorption lines. In general, winds of cool stars are subtle and difficult to detect. Far shortward extended wings due to the wind absorption have been observed in many Fe I lines of ρ Cas in the phase when $T_{eff}=7250$ K (Lobel et al. 1998). The upper limit of the mass-loss rate was derived as $9.2 \cdot 10^{-5} M_\odot \text{ yr}^{-1}$. We have also detected these wings in many lines in the near-UV (Fig. 3). In addition, we have also found violet wings extending up to 120 km s $^{-1}$ in the spectrum of HR 8752. Assuming $\log(L/L_\odot)=5.6$ (de Jager 1998) and $\rho=7 \cdot 10^{-15}$ gr cm $^{-3}$ as an upper limit of the density for the outermost layers of the atmosphere (from the model with $T_{eff}=7900$ K and $\log g=1.1$), we estimate from $\dot{M} = 4\pi R_* \rho V_\infty$ an upper limit $\dot{M}_{max}=6.7 \cdot 10^{-6} M_\odot \text{ yr}^{-1}$ assuming spherically symmetric mass loss. We derived for ρ Cas almost the same T_{eff} as it had in Dec. 21 1993 (Lobel et al. 1998). This suggests that ρ Cas makes small “oscillations” with an amplitude $\Delta T_{eff} \sim 500$ K near the void. However, the effective temperature of HR 8752 has risen sharply over the last decades and places the star on the border of the void. When deriving the mass loss rates we have assumed spherically symmetric outflow. However, one should keep in mind that the real distribution of the matter around these hypergiants is very complex and asymmetric (Lobel 1997, Petrov & Herbig 1992, Humphreys et

al. 1997).

It is very unlikely that the high effective temperature of HR 8752 is due to the extra heating produced by the secondary B1, which is located at 200 AU from the primary and has an orbital period of 500 yr (Piters et al. 1988). In that case, the overall spectrum of HR 8752 would be a combination of spectral lines formed in the hot upper layers (heated by the secondary) and cool inner layers (Piters et al. 1988). This is not observed and the spectrum is quite “normal”, as one would expect for a hypergiant with $T_{\text{eff}} \sim 8000$ K.

Understanding the final stages of stellar evolution of stars with $10 M_{\odot} \leq M_{\text{ZAMS}} \leq 60 M_{\odot}$ requires detailed knowledge of the atmospheric pulsations and mass-loss mechanisms of cool hypergiants. We are inclined to think that the large variations with $\Delta T_{\text{eff}} \sim 3000\text{--}4000$ K are not caused by pulsations but reflect some complex *evolutionary* changes due to the active reconstruction of the stellar interior. Just how enhanced mass loss occurs at bouncing, is not known. It seems significant that a number of stars moving to the blue is clustering at the low-temperature side of the void while none of them occurs inside the void. This leads to the hypothesis that when approaching the border of that area, the star may show excessive mass loss and the development of an envelope, associated with a reduction of the effective temperature. How frequently (maybe just once?) this will happen before the star eventually passes through the void is an open question. It is quite possible that the final passage of the most massive stars through the void never takes place and that these stars finally explode as Type II supernovae.

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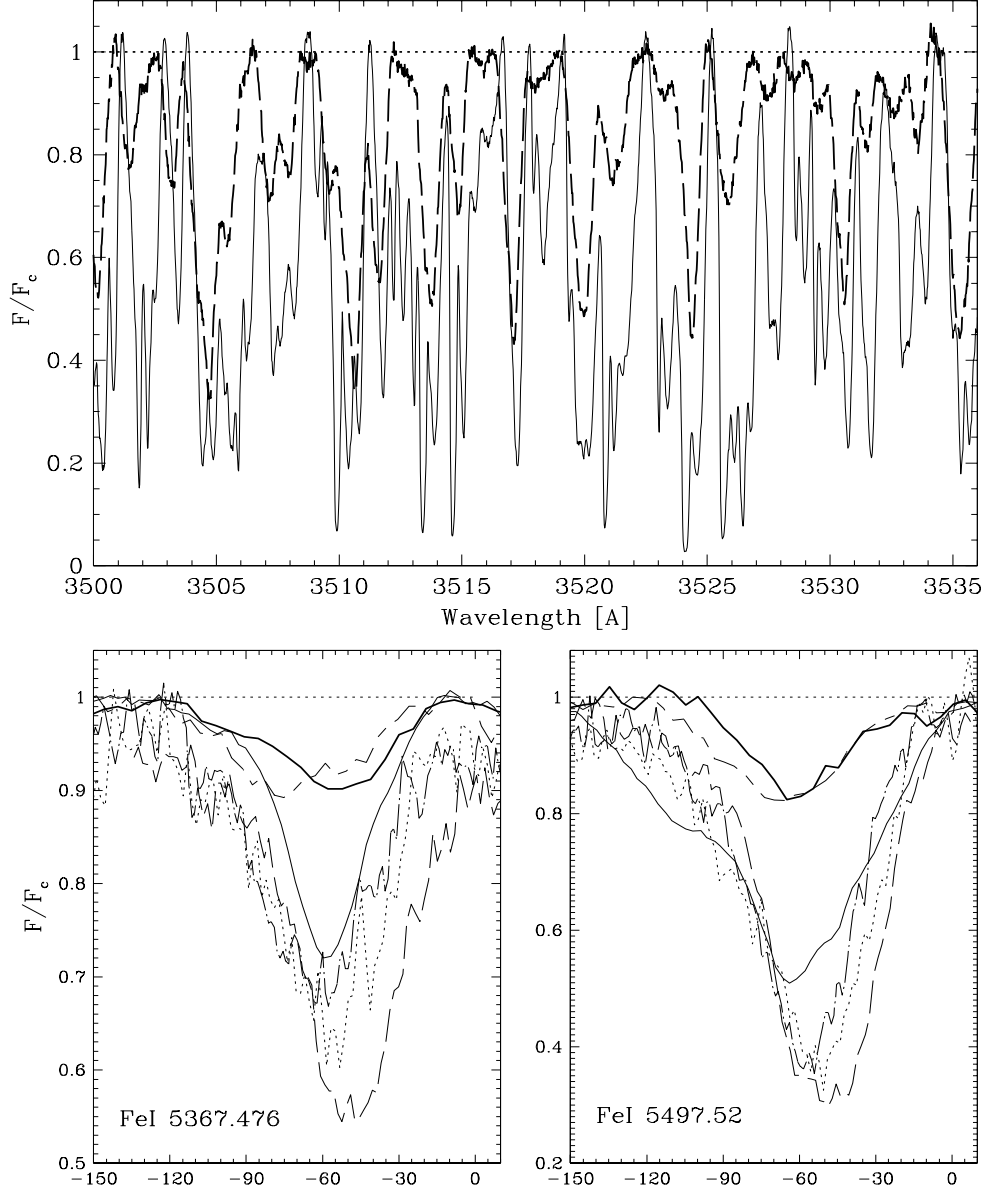


Fig. 1.— **upper panel:** High resolution near-UV spectra of HR 8752 (bold line) and of ρ Cas (thin line) observed on Aug. 4 '98 with UES. Note the single absorption cores in HR 8752 which appear to split in ρ Cas. **lower panels:** Two unblended FeI lines in both stars. The lines of HR 8752 developed violet wing extensions (bold line: NOT Oct. 1998, short dashed line: UES April 1995), which was also observed in ρ Cas in Nov.-Dec. 1993 when its $T_{\text{eff}}=7250$ K (thin line: UES). Note the strong weakening of these neutral lines over the past three decades (Dominion Obs.: long dashed line: Sept. 1969, dotted line: July 1975 and dash-dotted: Aug. 1978). The spectral resolutions are equal but note that both stars have different systemic velocities of -69 to -50 kms^{-1} and -47 ± 2 kms^{-1} respectively.

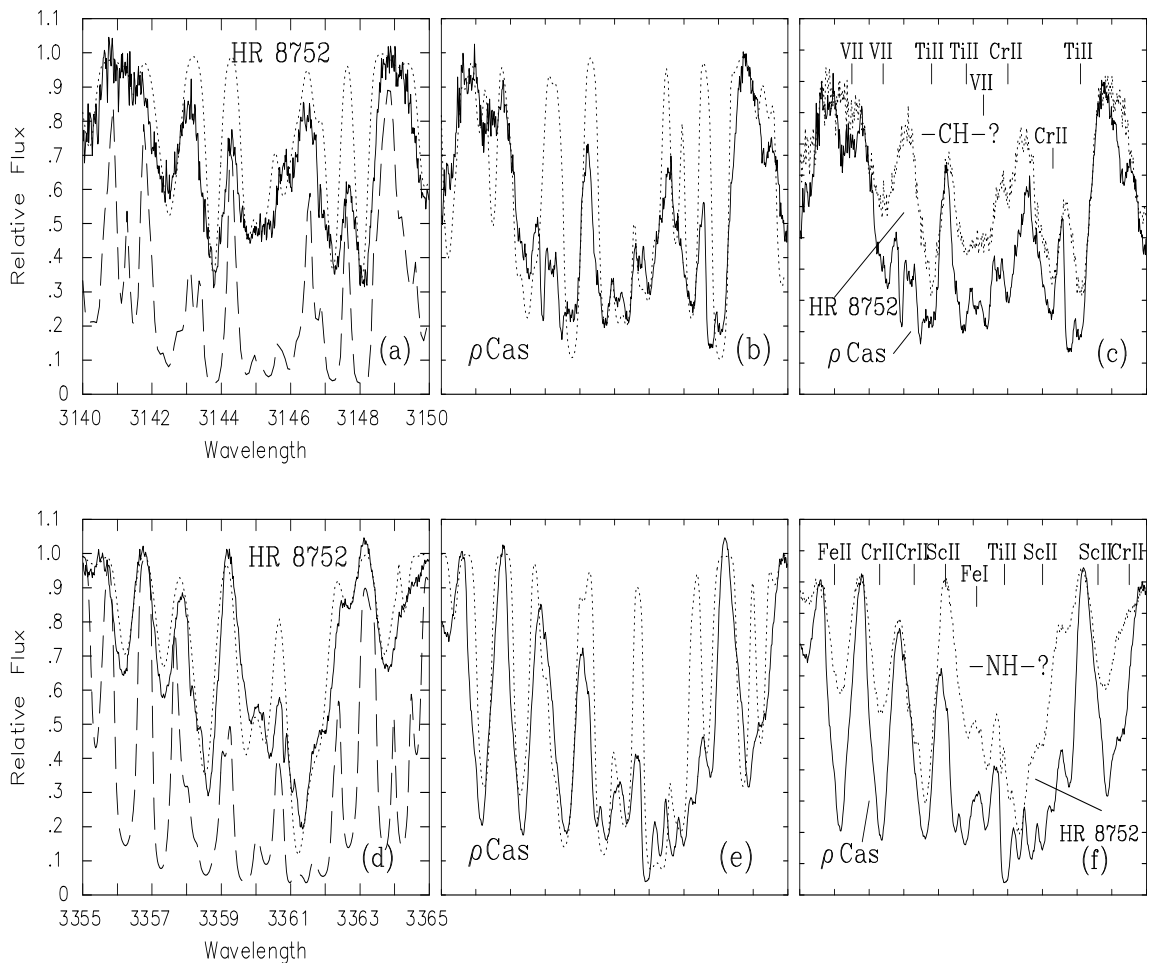


Fig. 2.— Theoretical (dotted lines) and observed (solid lines) spectra of the regions near the CH (top row) and NH (bottom row) molecular bands. Theoretical spectra are computed for $T_{\text{eff}}=8100$ K, $\log g=1.0$ for HR 8752 (panels (a) and (d)) and for $T_{\text{eff}}=7500$ K, $\log g=1.0$ for ρ Cas (panels (b) and (e)). These temperatures are the upper limits obtained from our analysis. Dashed lines in panels (a) and (d) correspond to the model $T_{\text{eff}}=6250$ K, $\log g=0.5$. In panels (c) and (f) we compare the observations of HR 8752 and ρ Cas. To illustrate the effect of rotation we have convolved the synthetic spectrum (dotted) in panel (d) with $v \sin i=20$ km s $^{-1}$. The observed spectra have been corrected for the system velocities.

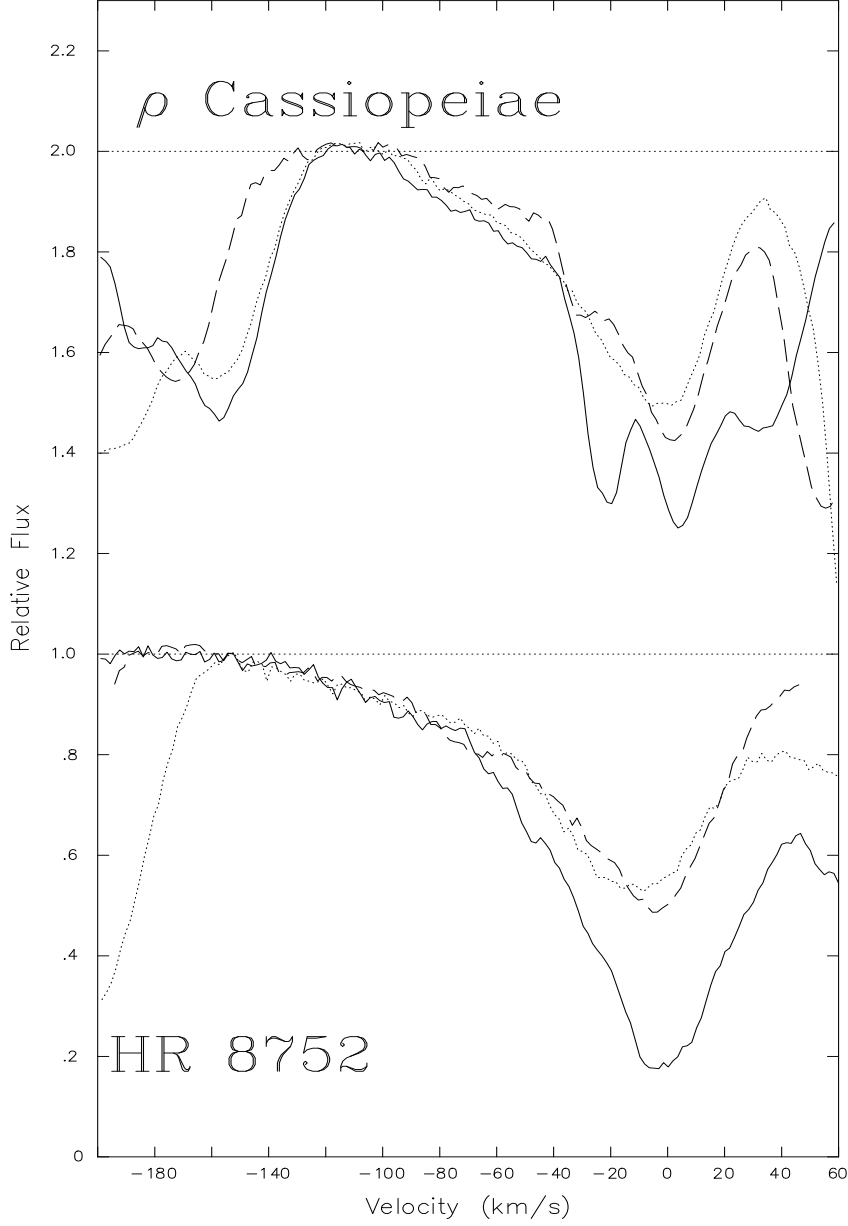


Fig. 3.— The violet-extended wings of Fe II 3448.43 (solid line), Fe II 3436.107 (dotted line) and Fe I 3640.390 Å (dashed line) lines in the spectrum of ρ Cas (shifted upwards by 1.0 in upper panel) and the violet wings of Ti II 3335.2 (solid line), Ti II 3500.34 (dashed line) and Si II 3862.6 Å (dotted line) in the spectrum of HR 8752 (lower panel). All lines have been shifted to their laboratory wavelengths.